Final Technical Report: EHP Geodetic Monitoring Operations

Cooperative Agreement Number: G15AC00065

Geodetic Monitoring Project Name: GPS Array for Mid-America Monitoring Deformation in the New Madrid Seismic zone

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Abstract

The GPS Array for Mid-America (GAMA) is a Continuous GPS network, that is now almost completely upgraded to Global Navigation Satellite System (GNSS) equipment, focusing on monitoring crustal deformation associated with the New Madrid seismic zone (NMSZ). It is also the only scientific, seismic hazard, focused continuous space based geodetic network with stable geodetic monuments in the central United States. GAMA samples the crust in the NMSZ sparsely at three scales: Fault, crustal and regional. Since its inception in 1998 through the NSF funded Mid-American Earthquake Center (MAEC), and its continued operation and maintenance since 2008 under the NEHRP USGS Cooperative Agreement (CA) for Geodetic Monitoring Operations, GAMA has provided open, unrestricted access to the GPS, and now GNSS, data, and has been used by several scientific groups in an active discussion about crustal deformation and seismic hazard in the region. The network also provides 1 Hz high-rate data in real-time though the Tennessee Department of Transportation, and 1 Hz and 5 Hz high-rate data on PBO significant event triggers.

Report:

Major Goal(s) & Activities of the Geodetic Project:

Goals: Continued operation of the GPS Array for Mid-America (GAMA, Cooperative Agreement Number: G15AC00065,Geodetic Monitoring Project Name: GPS Array for Mid-America Monitoring Deformation in the New Madrid Seismic zone during 3/1/2015-2/29/2020), to maintain network size, upgrade to full GNSS operations (change name to GNSS Array for Mid-America to keep acronym), and opportunistically grow the network when possible by acquire additional GNSS equipment through the USGS GN budget and U. of Memphis funds.

Activities: During the 5-year Cooperative Agreement we continued operation and maintenance of GAMA (Figure 1) with the base USGS GN budget and upgraded the network to GNSS receivers and antennas through a deferred maintenance USGS GN supplement. The previous network equipment recorded only GPS and the new equipment will record all four systems. The O&M also included hardening the stations for improved performance during disasters (ice storms, tornados, floods, earthquakes, etc.), and an opportunistic expansion by 2 stations. All GAMA stations are using the Internet for receiver control and data transfer, and all stations in the state of Tennessee also contribute to Tennessee Department of Transportation (TDOT) real time network.

Accomplishments & Changes Implemented in this Reporting Period:

The network grew from 13 to 15 stations with the formal transfer of the 2 University of Arkansas (UArk) stations (HCEX and PTGX – see table 1) to GAMA in 2018. These stations were installed in 2006 with drilled braced monuments by UArk to compare against the H beam monuments with funds from a USGS NEHRP grant. The funding was for 2 years. CERI had been providing infrastructure support and maintaining these stations without support from the USGS, but they are now officially part of GAMA and their early data has been submitted to the UNAVCO Archive by UArk. Transferring these stations to GAMA was important as it allowed them to be included in the deferred maintenance upgrade to GNSS equipment. We have installed the GNSS upgrade at 9 of the 15 stations to the new UNAVCO/PBO selected GNSS receiver the Septentrio PolaRx5 and PolaNt-x MF High Performance Multi-Frequency antenna. One of the stations that is not upgraded is waiting for warranty repair at the factory of one of the new Septentrio receivers. The other five sites had a small Freewave based network that did not have the bandwidth to support the Septentrio receivers. The plan was to replace this network with a new network using consumer Wi-Fi equipment at ~$100/unit, but the new Wi-Fi units did not work (even though the Freewaves worked on the same frequency with the same antennas). All the sites in this subnetwork were upgraded temporarily from Trimble NetRS to Trimble NetR9 receivers. Life safety quality Wi-Fi equipment, which is also used by the seismic networks (~$1600/unit), was acquired and the system is built and ready to be installed. The new Septentrio GNSS equipment is also ready to be installed at those stations at the same time. We have all the equipment to complete the upgrade.

During the penultimate review for GN network support (the review for this CA) it was suggested/recommended that we opportunistically expand the network using a combination of replacement equipment acquisition funds (there are funds for 1 receiver and antenna/yr to replace equipment that has failed, but some years don't have a failure) and residual funds when available. Under this plan, two new stations using a combination of GN network and CERI funds were sited and installed (in addition to the cost of the GNSS equipment there is also the cost for the monument to mount the antenna, and these are ~2x the equipment cost as we have to use a deep drilled, braced monument due to the sediments of the Mississippi Embayment), bringing the current total station count to 17. The first station installed is hosted by the Armorel Public Schools in Armorel, AR, and forms a triangular subnetwork across the main axial strike-slip branch of the NMSZ. Armorel was the first GAMA station with Septentrio equipment recording full GNSS data. It is solar powered and uses donated Internet service through the school. It connects to the school over a short, consumer Wi-Fi link. A second new station was installed in bedrock at the South Central Correctional facility in Clifton, TN. This station completes the long-desired network geometry providing a regional triangular sampling around the New Madrid seismic zone on bedrock sites. This station has a mast bolted into rock. The station is also solar powered. It is currently without communications. The equipment to connect with a local community college, which has agreed to donate Internet service, through a solar powered repeat using the prison's water tower, is ready to be installed. Since we have all new GNSS equipment, some still under warranty, we should have one extra receiver and antenna this year and have been investigating expanding into the eastern Tennessee Seismic zone (also suggested in the review). We have found a few sites with suitable rock outcrop and sky view, but need to find a communications solution with a direct, or single repeat, Wi-Fi link to the internet. Rock site stations are much cheaper (<$1K for the monument), which makes them easier to acquire.

The most challenging problem for station siting is communications. Very few "ideal" antenna sites are within a reasonable cable run to the Internet, which is also the Achilles heel of the network as the Internet is typically one of the first pieces of infrastructure to fail in the case of an earthquake. Some sort of robust wireless communications between the GNSS equipment and the Internet point of presence is often required, but this is relatively easy to provide at the station side.

Contributions to overarching goals of the GN component of EHP program

Through long-term monitoring for interseismic deformation GAMA is currently only able to set an upper limit to the interseismic strain rate. How interplate earthquakes are driven is a controversial issue and it is clear that the plate boundary elastic rebound model does not work to explain intraplate earthquakes. A number of driving mechanisms have been proposed, some of which predict relatively local surface deformations that may be above the GNSS noise floor. GAMA has observed the loading response to hydrological loading from floods. Two small subnetworks could observe fault creep and transient phenomena on the Reelfoot thrust, where there is a 4 station linear profile across the fault, or across the seismically defined, strike-slip, axial fault, where there is a triangular subnet spanning the fault, if deformation occurs at a rate above the GNSS noise floor.

The use of real-time and near real-time data for earthquake likelihood forecasting in the NMSZ is currently cost prohibitive. Reliable real-time communications can only be provided by satellite. With low power, small size equipment such as BGAN, establishing such communications is technologically relatively easy, but prohibitively expensive especially if one has to transmit the full phase data to a processing center for processing on arrival. Additionally, the processing center should be outside the region expected to be affected by a large NMSZ earthquake. This will prevent the type of failure that occurred in the 2010 Maule, Chile, earthquake where the processing and satellite receiving centers were knocked out by the earthquake and the data was lost. If one can obtain mm accuracy in the GNSS receiver, using some (expensive?) correction service that should also use satellite communications, one may be able to send the location data, or modeled earthquake parameters, back through the satellite at a cost lower than the full phase data information (but cost is a question).

CERI does not perform, real-time high-rate GPS processing or time series modeling, or daily position solutions. The USGS and Nevada processing centers both process and publish daily, or shorter time span, average position and velocity products for the stations in GAMA. These solutions are suitable for QC monitoring and a weak determination of displacement and velocity, but not suitable for detailed analysis. Nevada for example, processes over 16K stations per day and cannot solve problems at individual sites. To try and resolve very small, slow velocities and strains requires optimizing the processing for the NMSZ under very high data QC standards. Due to the small amplitudes of the deformation rates in the NMSZ, CERI does batch processing to obtain the most precise estimations of velocity and strain rather than the most rapid estimations, and the temporal resolution and latency is too long to be useful for real-time applications.

GAMA currently operates continuously at 1 Hz, but does not go faster due to data communication bandwidth limitations and storage costs. The 1 Hz data have been used to examine long period surface waves from the Sumatra, Maule and Tohoku-Oki earthquakes in a post-processing mode. One GNSS station is collocated with a broadband seismic station which provided an opportunity to compare absolute GPS seismograms for the three earthquakes to the seismogram from the seismic station. Unfortunately, what makes a good seismic station (we have at least one in a cave) oftentimes does not make a good GNSS station, especially if the above ground GNSS station infrastructure puts noise into the ground around the seismic station.

Map of Geodetic Stations:

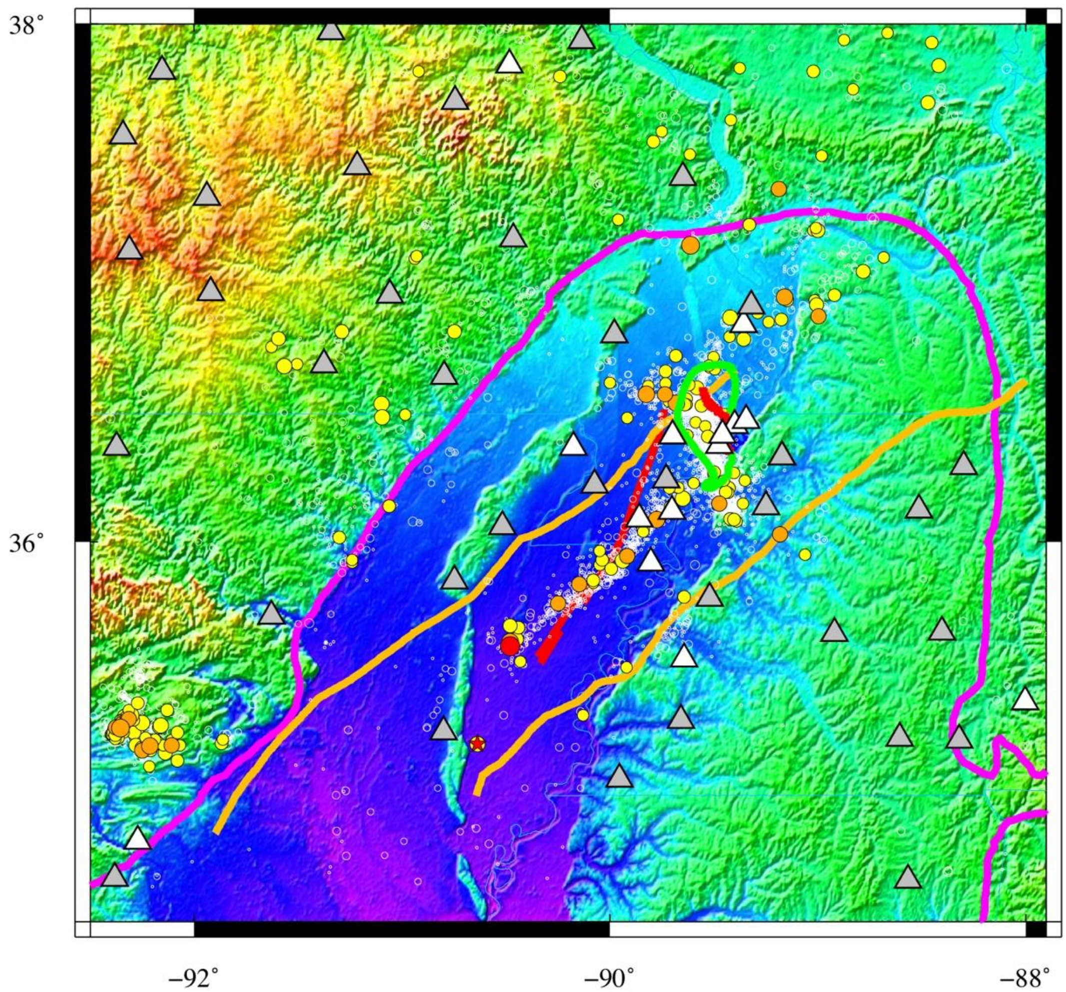

Figure 1. Map showing the open GAMA continuous GNSS stations (white triangles), and other, mostly open, GPS/GNSS stations (gray triangles) almost all with non-geodetically mounted antennas – typically on a roof or fence post. Earthquakes shown by colored circles, red M=5, orange 4≤M<5, yellow 3≤M<4, white 2≤M<3, and gray M<2. The Mississippi Embayment is shown by the magenta line. The buried Reelfoot Rift boundaries are shown by orange lines. Surface features shown include the Lake county uplift over the Reelfoot Fault in green, the Reelfoot Scarp and the Bootheel lineament or fault are shown by the NW-SE and NNE-SSW striking red lines respectively. GAMA samples potential crustal deformation at the scale of the faults, across the Reelfoot thrust and axial faults, with spacings of 5-10 km, the crust, with spacings 30-50 km, and regionally, at 1-200 km. Color, shaded topography from 30 sec SRTM showing the extreme flatness of the Mississippi River flood plain in the central part of the Mississippi Embayment.

Publications

The known publications, post 2007 when the USGS began supporting the network, that analyze data from GAMA, or use position or velocity products derived from GAMA are listed below. The data from GAMA are archived and openly distributed by the UNAVCO GPS/GNSS Archive that actively encourages acknowledging itself. Until recently, DOIs were not assigned to the data at the UNAVCO Archive and data sources and funding were not well documented individually, so acknowledgements to the open GPS/GNSS data hosted at the UNAVCO Archive were usually to the UNAVCO Archive only. Even with DOIs for networks and stations, and a statement on the UNAVCO Archive server to use them, the vast majority of publications, even by data contributors, still only reference the UNAVCO Archive, not the source of the data itself. The idea that "open" data means it does not need to be acknowledged seems to be internalized in the space geodetic and seismic communities. In addition, publications about events such as the 2017 Great America Eclipse, that analyzed data from up to 4,000 GPS/GNSS stations in the U.S., only acknowledge the data hosting services as no publisher will consider a manuscript with hundreds of data references.

PI Smalley first or co-author.

Peer-Reviewed publications

Jessica R. Murray, Noel Bartlow, Yehuda Bock, Benjamin A. Brooks, James Foster, Jeffrey Freymueller, William C. Hammond, Kathleen Hodgkinson, Ingrid Johanson, Alberto López-Venegas, Dörte Mann, Glen S. Mattioli, Timothy Melbourne, David Mencin, Emily Montgomery- Brown, Mark H. Murray, Robert Smalley, and Valerie Thomas, Regional Global Navigation Satellite System Networks for Crustal Deformation Monitoring, Seismological Research Letters Volume XX, Number XX – 2019, doi: 10.1785/0220190113.

Boyd, O. S., Smalley, R., and Zeng, Y. (2015), Crustal deformation in the New Madrid seismic zone and the role of postseismic processes, J. Geophys. Res. Solid Earth, 120, 5782– 5803.

Smalley, R. Jr., M.A. Ellis, Space Geodesy and the New Madrid seismic zone: An enigma within an enigma, EOS, 89, 28, 256, 2008.

Abstracts

Demian Gomez, Robert Smalley Jr, GPS Virtual Array Beamforming of Ionospheric Total Electron Content Disturbances Associated with Solar Eclipses, Abstract SA23C-3132, presented at 2019 Fall Meeting, AGU, San Francisco, CA, 9-13 Dec.

Amosu, A., R. Smalley, J. Puchakayala, Modeling Earth's Crustal Deformation In The Lower Mississippi River Basin, SSA Annual Meeting, SRL 84:2 Pg. 376, (2013).

Amosu, A., R. Smalley, J. Puchakayala, Modeling Earth Deformation from the 2011 Inundation in the Mississippi River Basin using Hydrologic and Geodetic Data, Abstract G41A-0891, presented at 2012 Fall Meeting, AGU, San Francisco, Calif. Dec 3-7, 2012.

Davis, J. P. D., and Smalley, R., Noise Reduction in High-Rate GPS Seismograms by Array Phase Match Filtering. Seis. Res. Lett, 82, , 353, 2011.

O.S. Boyd, Y. Zeng, L.R. Guzman, R. Smalley, Do small surface strains in the New Madrid seismic zone reflect a physical process? Abstract, G43C-01, presented at 2011 Fall Meeting, AGU, San Francisco, Calif. 5-9 Dec, 2011.

Smalley, R., Bevis, M., Brown, A., Puchakayala, J., and Davis, J., New Madrid Seismic Zone Deformation Field from the GPS Array for Mid-America. Seis. Res. Lett, 82, , 324, 2011.

Thesis

Adewale Moroof Amosu, Elastic Deformation of the Earth's crust from surface loading phenomena, Ph.D. Thesis, The University of Memphis, 117 pp., May 2014.

Known Publications using GAMA network data by authors other than the PI

Craig, T.J., Chanard, K. & Calais, E., Hydrologically-driven crustal stresses and seismicity in the New Madrid Seismic Zone. Nat Commun, 8, 2143 (2017). https://doi.org/10.1038/s41467-017-01696-w.

Calais, E., T. Camelbeeck, S. Stein, M. Liu and T.J. Craig, A New Paradigm for Large Earthquakes in Stable Continental Plate Interiors, Geophys. Res. Letters, 43, doi:10.1002/2016GL070815, 2016.

Craig, T. J., and E. Calais, Strain accumulation in the New Madrid and Wabash Valley seismic zones from 14 years of continuous GPS observation, J. Geophys. Res. Solid Earth, 119, doi:10.1002/2014JB011498, 2014.

Hamburger, M.W., Boyd, O.S., Calais, E., King, N.E., and Stein, S.A., 2014, Advancing geodesy in the U.S. Midcontinent-Workshop report, U.S.G.S. Open-File Report 2014-1169, 22 p.

Boyd, O., E. Calais, J. Langbein, H. Magistrale, S. Stein, and M. Zoback, Workshop on New Madrid Geodesy and the Challenges of Understanding Intraplate Earthquakes, U.S.~Geological Survey Open-File Report 2013-0031, 184~p., 2013.

Calais, E., and S. Stein, Space geodetic evidence for time-variable deformation in the New Madrid seismic zone, Science, 323, 10.1126/science.1168122, 2009.

Höwer, B., B. Gundlich, M. Karegar, and J. Kusche, GPS Time Series Analysis in the New Madrid Seismic Zone, Geophysical Research Abstracts, Vol. 21, EGU2019-16814, 2019, EGU General Assembly 2019.

Geodetic Project Website:

www.ceri.memphis.edu/people/gps

Data Archiving and Availability

All stations now have donated Internet communications and downloading the daily 15 second files is done automatically to the UNAVCO Facility Archive. These data are available immediately from the UNAVCO Archive.

High rate (1 Hz) downloads are done daily by CERI with local archiving. We also record at 5 Hz and the 1 and 5Hz data are download by UNAVCO on PBO triggers.

RINEX data (15 sec epochs, plus 1 sec and 5 Hz during PBO triggers) are available from
http://facility.unavco.org/data/gnss/perm_sta.php
filter by network, using network code GAMA.
Continuous 1 Hz data available from CERI on request.

TDOT also receives the 1 Hz data in real-time, also over the Internet, and this data is available from TDOT in real-time (but is not free).

Table 1: Metadata for GPS Stations

A: Station/monument information for GPS stations:

Station name	code	station type	Monument	Install date
Reelfoot Lake State Park	RLAP	C- GPS	I-Beam	10/15/97
Northwest Corrections Center	NWCC	C- GPS	I-Beam	07/11/00
Steele Airport	STLE	C- GNSS	I-Beam	04/27/00
McCarty R-3 School	MCTY	C- GNSS	I-Beam	04/21/00
Piggot water treatment plant	PIGT	C- GNSS	I-Beam	02/26/00
Delta Research Center	PTGV	C- GNSS (collocated with PTMO broadband seismic station)	I-Beam	03/11/99
Delta Research Center	PTGX	C- GNSS	DBM	06/01/06
Mississippi County Airport	MAIR	C- GNSS PS	I-Beam	02/26/00
Camp JT Robinson	CJTR	C- GNSS	Steel mast in rock	09/15/99
Hill Crest Elementary School	HCES	C- GNSS	I-Beam	08/17/00
Hill Crest Elementary School	HCEX	C- GNSS	DBM	07/07/06
Covington Middle School	CVMS	C- GPS	I-Beam	06/22/00
Mineral Area College	MACC	C- GNSS	Steel mast in rock	10/13/99
New Markham	NMKM	C- GPS	DBM	01/09/08
Lake County High School	LCHS	C- GPS	DBM	01/09/08
Armorel School District	ARML	C-GNSS	DBM	02/25/18
South Central Correctional Facility	SCCF	C-GNSS	Steel mast in rock	11/25/19

B: Station location information for GPS stations:

City	County	St	X (m)	Y (m)	Z (m)	Lat (N)	Lon (E)	Elev (m)
Tiptonville	Lake	TN	58663.96	-5134604.22	3770669.30	36.474	-89.345	58.47

Tiptonville	Lake	TN	48583.29	-5138518.71	3765529.06	36.417	-89.458	64.92
Steele	Pemiscot	MO	12827.29	-5160199.99	3736229.95	35.906	-89.857	50.44
McCarty	Pemiscot	MO	26808.67	-5158166.70	3738951.17	36.119	-89.702	51.61
Piggott	Clay	AR	-15723.78	-5141765.76	3761385.19	36.370	-90.175	55.32
Portageville	New Madrid	MO	26938.23	-5138875.51	3765245.17	36.413	-89.700	58.09
Charleston	Mississippi	MO	57369.54	-5109959.40	3803820.24	36.847	-89.357	67.52
North Little Rock	Pulaski	AR	-207900.95	-5237733.64	3621714.98	34.822	-92.273	126.07
Troy	Obion	TN	74358.65	-5143751.66	3758031.33	36.333	-89.172	77.99
Covington	Tipton	TN	32327.59	-5195705.17	3686948.89	35.451	-89.644	73.01
Park Hills	St. Francois	MO	-42649.83	-5042996.72	3892013.17	37.845	-90.485	220.06
Tiptonville	Lake	TN	53749.88	-5135969.69	3768904.29	36.271	-89.400	58.00
Tiptonville	Lake	TN	47367.49	-5141175.77	3761937.64	36.193	-89.472	62.00
Armorel	Mississippi	AR	17789.99	-5171398.17	3720791.79	35.917	-89.803	50.03
Clifton	Wayne	TN	181647.42	-5203414.13	3671849.23	35.373	-88.001	95.89

Table 2: Equipment metadata (installations, changes, etc.) current to 2/29/2020.

Code	Date	Description	Receiver type	Receiver S/N	FW	Antenna type	Antenna S/N	Ant Ht, m
ARML	1/25/2018	Install	Septentrio PolaRx5	3012392	5.1.0	Septentrio PolaNt-x MF Model AT1675-540S	9516	0
ARML	9/24/2019	Update FW	Septentrio PolaRx5	3012392	5.3.0			
CVMS	06/01/00	Install	Ashtech Z-12	LP03440		ASH700936D_M w/ Snow Dome	CR520000405	0
CVMS	7/16/03	Change receiver	Ashtech Micro-Z	ZR220022401		ASH700936D_M w/ Snow Dome	CR520000405	0
CVMS	1/23/04	Change receiver	Ashtech Micro-Z	UC200316025				0
CVMS	6/22/06	Change receiver	Ashtech Micro-Z	ZR220022413				0
CVMS	1/13/07	Change receiver	Ashtech Micro-Z	ZR220022401				0
CVMS	1/27/07	Update FW	Ashtech Micro-Z	ZR220022401	CK00			
CVMS	3/2/07	Change receiver	Trimble NetRS	4646125547				
CVMS	6/26/07	Change Radome				ASH700936D_M Radome SCIS 0412	CR520000405	0
CVMS	05/17/10	Change receiver	Trimble NetR8	5013K66509	4.14			
CVMS	09/18/10	Update FW	Trimble NetR8	5013K66509	4.17			
CVMS	10/17/10	Change Receiver	Trimble NetR8	5010K66014	4.17			
CVMS	2/28/11	Update FW	Trimble NetR8	5010K66014	4.19			
CVMS	5/26/11	Update FW	Trimble NetR8	5010K66014	4.41			
CVMS	8/03/12	Change receiver	Trimble NetR9	5044K71324	4.60			
CVMS	2/25/14	Change antenna, same radome				PN - 701945-01 Rev B ASH701945B_M Radome SCIS 0412	CR519991709	
CVMS	2/25/14	Update FW	Trimble NetR9	5044K71324	4.62			
CVMS	3/31/15	Update FW	Trimble NetR9	5044K71324	4.70			
CVMS	5/14/2019	Changed Antenna				Trimble Zephyr II	1441107459	0
CVMS	6/27/2018	Radome replaced				PN - 701945-01 Rev B ASH701945B_M Radome SCIS 0303	CR519991709	0

CRAR	8/1/1999	Install	Ashtech Z-12	LP01664		ASH700936D_M w/ Snow Dome	CR16943	0
CJTR	2/13/04	Rename CRAR to CJTR	Ashtech Z-12	LP01664		ASH700936D_M w/ Snow Dome	CR16943	0
CJTR	3/14/07	Change receiver	Trimble NetRS	4644124587	1.1-5			
CJTR	12/10/07	Change Radome				ASH700936D_M SCIS Radome 0428	CR16943	
CJTR	11/30/09	Internet comms established	Trimble NetRS	4644124587	1.1-5			
CJTR	5/10/11	Update FW	Trimble NetRS	4644124587	1.3-1			
CJTR	7/16/15	New receiver and antenna	Trimble NetR9	5349K48409	4.93	ASH701945D_M SCIS Radome 0428	CR519991814	
CJTR	3/2/2017	Update Fw	Trimble NetR9	5349K48409	5.20	ASH701945D_M SCIS Radome 0428	CR519991814	
CJTR	6/4/2019	Changed antenna, receiver	Septentrio PolaRx5	3046692	5.2.0	PolaNT-x No radome	14506	0
CJTR	9/24/2019	Update Fw			5.3.0			
HCES	08/17/00	Install	Ashtech Z-12	LP00493		ASH700936D_M w/ Snow Dome	CR520002502	0
HCES	6/13/02	Change receiver	Ashtech Z-12	LP019992705				0
HCES	2/4/05	Change receiver	Trimble NetRS	4427235630	1.0-3			0
HCES	5/18/05	Change receiver	Trimble NetRS	4431236751	1.1-2			0
HCES	6/21/05	Update FW	Trimble NetRS		1.1-3			0
HCES	6/29/05	Change receiver	Trimble NetRS	4429236312	1.1-2			
HCES	7/7/05	Replace radome				ASH700936D_M Replaced SNOW radome	CR520002502	0
HCES	3/20/06	Update FW	Trimble NetRS	4429236312	1.1-5			
HCES	6/11/07	Change Radome				ASH700936D_M SCIS Radome 0303	CR520002502	0
HCES	7/5/09	Change receiver	Trimble NetRS	4632120758	1.1-5			
HCES	5/8/11	Update FW	Trimble NetRS	4632120758	1.3-1			
HCES	2/16/12	Change receiver	Trimble NetR9	5044K71324	4.43			
HCES	4/11/12	Change receiver	Trimble NetRS	4632120758	1.3-1			
HCES	5/19/16	Change Antenna				TRM57971.00 No radome	1441107459	0

HCES	5/16/2017	Update FW	Trimble NetRS	4632120758	1.3-2			
HCES	5/14/2019	Receiver antenna swap	Septentrio PolaRx5	3046396	5.2.0	Septentrio PolaNt-x MF No radome	14417	0
HCES	9/24/2019	Fw update			5.3.0			
HCEX	7/7/2006	Install	Trimble NetRS	4451241712	1.1-3	ASH701945E_M SCIT	CR520023315	0.083
HCEX	7/9/2006	Update FW	Trimble NetRS	4451241712	1.1-5	ASH701945E_M SCIT	CR520023315	
HCEX	8/7/2009	Receiver antenna swap	Trimble NetRS	4921173189	1.1-5	ASH701945C_M SCIT	CR520012401	0.083
HCEX	11/14/2009	Change receiver	Trimble NetRS	4451241712	1.1-5			
HCEX	5/25/2011	Update FW			1.3-1			
HCEX	8/29/2012	Monument struck				ASH701945C_M	CR520012401	0.0083
HCEX	9/23/2015	Change Antenna				TRM29659.00	220062093	0.0083
HCEX	5/16/2017	Update FW			1.3-2			
HCEX	5/14/2019	Receiver antenna swap	Septentrio PolaRx5	3046498	5.2.0	Septentrio PolaNt-x	14419	0
HCEX	6/3/2019	Receiver swap	Septentrio PolaRx5	3022876	5.2.0			
HCEX	9/24/3019	Fw Update			5.3.0			
LCHS	1/10/08	Install	Trimble NetRS	4431236763	1.1-5	ASH700936D_M SCIS Radome 0466	CR520002501	0.075
LCHS	4/29/11	Update FW	Trimble NetRS	4431236763	1.3-1			
LCHS	2/16/12	Change receiver	Trimble NetR9	5112K74584	4.43			
LCHS	4/24/15	Update FW	Trimble NetR9	5112K74584	4.70			
LCHS	7/30/15	Change receiver	Trimble NetRS	4646125551	1.3-1			
LCHS	5/16/2017	Update FW	Trimble NetRS	4646125551	1.3-2			
LCHS	5/14/2019	Receiver Antenna swap	Septentrio PolaRx5	3046609	5.2.0	Septentrio PolaNt-x MF No radome	14494	0
LCHS	9/28/2019	Fw Update			5.3.0			
MACC	10/13/1999	Install	Ashtech Z-12	LP019992705	CD00	ASH700936D_M w/ Snow Dome	11755	0
MACC	7/25/01	Change receiver	Ashtech Z-12	LP01766	CD00	ASH700936D_M	CR520000601	0
MACC	3/30/05	Change receiver	Trimble NetRS	4427235628	1.1-1			
MACC	5/19/05	Change receiver	Trimble NetRS	4427235647	1.1-1			
MACC	6/22/05	Change receiver	Trimble NetRS	4427235647	1.1-3			

MACC	6/30/05	Update FW	Trimble NetRS	4427235647	1.1-2			
MACC	3/20/06	Update FW	Trimble NetRS	4427235647	1.1-5			
MACC	7/13/07	Change Radome				ASH700936D_M Radome SCIS 0429	CR520000601	0
MACC	11/24/08	Change receiver	Trimble NetRS	4646125551	1.1-5			
MACC	4/29/11	Update FW	Trimble NetRS	4646125551	1.3-1			
MACC	7/15/11	Change Antenna				ASH700936D_M Radome SCIS 0429	CR520000401	0
MACC	9/5/12	Change LNA in antenna, no change to antenna serial number. No serial number on LNA.					CR520000401	0
MACC	3/25/15	Changed receiver and antenna	Trimble NetR9	5347K47846	4.81	TRM57971.00 No radome	5000112538	
MACC	3/31/15	FW update	Trimble NetR9	5347K47846	4.93			
MACC	3/2/2017	FW update	Trimble NetR9	5347K47846	5.20			
MACC	5/22/2019	Receiver Antenna swap	Septentrio PolaRx5	3046497	5.2.0	Septentrio PolaNt-x No radome	14507	0
MACC	10/17/2019	Receiver swap	Septentrio PolaRx5	3046396	5.3.0			
MAIR	2/1/00	Install	Ashtech Z-12	LP03379	CC00	ASH700936D_M w/ Snow Dome	CR520000408	0
MAIR	5/5/04	Change receiver	Ashtech Z-12	LP00491				
MAIR	6/2/04	Change receiver	Ashtech Z-12	LP03371				
MAIR	8/31/04	Change receiver	Ashtech Z-12	LP0379				
MAIR	2/10/06	Change receiver	Ashtech Micro-Z	ZR220022401				
MAIR	9/09/06	Change receiver	Trimble Trimble NetRS	4612261949	1.1-5			
MAIR	6/4/07	Change Radome				ASH700936D_M Radome SCIS 0418	CR520000408	0
MAIR	06/16/08	Wireless comms installed	Trimble NetRS	4612261949	1.1-5			

MAIR	5/10/11	Update FW	Trimble NetRS	4612261949	1.3-1			
MAIR	9/4/12	Change receiver	NetR9	5206K82035	4.61			
MAIR	3/31/15	FW update	Trimble NetR9	5206K82035	4.85			
MCTY	3/1/00	Install	Ashtech Z-12	LP03376		ASH700936D_M w/ Snow Dome	11782	0
MCTY	2/3/05	Change receiver	Trimble NetRS	4435237654	1.0-3			
MCTY	5/18/05	Change receiver	Trimble NetRS	4435237668	1.1-2			
MCTY	6/22/05	Update FW	Trimble NetRS	4435237668	1.1-3			
MCTY	6/29/05	Change receiver	Trimble NetRS	4435237654	1.1-2			
MCTY	8/8/05	Change receiver	Trimble NetRS	4427235628	1.1-2			
MCTY	3/20/06	Update FW	Trimble NetRS	4427235628	1.1-5			
MCTY	6/12/07	Change Radome				ASH700936D_M Radome SCIS 0423	11782	
MCTY	12/11/07	Change receiver	Trimble NetRS	4646125551	1.1-5			
MCTY	9/28/08	Change receiver	Trimble NetRS	4427235628	1.1-5			
MCTY	6/6/09	Change receiver	Trimble NetRS	4644124586	1.1-5			
MCTY	10/01/10	Update FW	Trimble NetRS	4644124586	1.3-0			
MCTY	3/3/11	Change receiver	Trimble NetR8	5013K66509	4.19			
MCTY	5/7/11	Update FW	Trimble NetR8	5013K66509	4.41			
MCTY	10/24/13	Change Receiver	Trimble NetR9	5238K52489	4.46			
MCTY	2/14/14	Change receiver and antenna	Trimble NetR9	5302K56776	4.62	ASH700936D_M SCIS Radome 0423		0
MCTY	3/30/15	Update FW	Trimble NetR9	5302K56776	4.93			
MCTY	3/2/2017	Update FW	Trimble NetR9	5302K56776	5.03			
MCTY	5/8/2019	Receiver Antenna swap	Septentrio PolaRx5	3046402	5.2.0	SEPPOLANT_X _MF No radome	14495	0
MCTY	10/2/2019	Receiver swap	Septentrio PolaRx5	3023116	5.3.0			
NMKM	1/10/08	Install	Trimble NetRS	4718131954	1.1-5	ASH701945C_M Radome SCIS 0460	CR620013601	0.075
NMKM	5/26/09	Change receiver	Trimble NetRS	4427235647	1.1-5			

NMKM	5/8/11	Update FW	Trimble NetRS	4427235647	1.3-1			
NMKM	10/5/12	Change receiver	Trimble NetRS	4431236763	1.3-1			
NMKM	5/16/2017	Update FW	Trimble NetRS	4431236763	1.3-2			
NMKM	6/3/2019	Receiver swap	Trimble NetR9	5302K56776	5.03			
NWCC	07/11/00	Install	Ashtech Z-12	LP03375	CD00	ASH700936D_M w/ Snow Dome	CR520000573	0
NWCC	09/07/00	Change receiver	Ashtech Z-12	LP01776		PN-701945-01 Rev C, ASH700936C_M w/ Snow Dome	CR520000503	0
NWCC	7/20/01	Change receiver	Ashtech Z-12	LP03371				
NWCC	5/15/04	Change receiver	Ashtech Z-12	LP00463				
NWCC	6/20/05	Change receiver	Ashtech Z-12	LP01766				
NWCC	3/7/07	Change receiver	Trimble NetRS	4646125548	1.1-5			
NWCC	6/5/07	Change Radome				PN-701945-01 Rev C, ASH700936C_M Radome SCIS 0420	CR520000503	0
NWCC	04/23/07	Internet comms established	Trimble NetRS	4646125548	1.1-5			
NWCC	5/9/11	Update FW	Trimble NetRS	4646125548	1.3-1			
NWCC	2/11/15	Replace antenna				TRM57971.00 No Radome	1441009473	
NWCC	4/13/2017	Replace antenna				TRM57971.00 No Radome	5000112568	
NWCC	5/16/2017	Update FW	Trimble NetRS	4646125548	1.3-2			
NWCC	6/3/2019	Receiver swap	Trimble NetR9	5207K82122	4.85			
PIGT	2/1/00	Install	Ashtech Z-12	LP00491	CD00	ASH700936D_M w/ Snow Dome	CR520000401	0
PIGT	10/15/03	Change receiver	Ashtech Z-12	LP03375	CD00	ASH700936D_M	CR520000404	0
PIGT	2/24/06	Change receiver	Micro-Z	UC1200316023	CN00			
PIGT	12/1/06	Change receiver Internet comms established	Trimble NetRS	4427235630	1.1-5			
PIGT	7/13/07	Change Radome				ASH700936D_M Radome SCIS 0410	CR520000404	0

PIGT	10/18/10	Change receiver	Trimble NetRS	4646125547	1.3-0			
PIGT	5/20/11	Update FW	Trimble NetRS	4429236312	1.3-1			
PIGT	11/29/12	Change receiver	Trimble NetR8	5010K66014	4.48			
PIGT	1/29/15	Change antenna				ASH700936D_M Radome SCIS 0410	CR1991783	0
PIGT	3/2/2017	Update FW	Trimble NetR8	5010K66014	48.01			
PIGT	3/9/2017	Replace Receiver	Trimble NetR9	5112K74584	5.20			
PIGT	5/21/2019	Receiver antenna swap	Septentrio PolaRx5	3046567	5.2.0	Septentrio PolaNt-x MF No radome	14425	0
PIGT	10/17/2019	Receiver swap	Septentrio PolaRx5	3046402	5.3.0			
PTGV	3/1/1999	Install	Ashtech Z-12	LP00491		ASH700936D_M w/ Snow Dome	11767	0
PTGV	8/7/1999	Update FW	Ashtech Z-12	LP00491	CC00			
PTGV	1/12/00	Change receiver	Ashtech Z-12	LP03423				
PTGV	5/13/02	Change receiver	Ashtech Z-12	LP03429				
PTGV	12/20/04	Change receiver	Trimble NetRS	4427235628	1.0-3			
PTGV	5/19/05	Change receiver	Trimble NetRS	4424234797	1.0-3			
PTGV	6/22/05	Update FW	Trimble NetRS	4424234797	1.1-3			
PTGV	6/30/05	Update FW	Trimble NetRS	4424234797	1.1-2			
PTGV	1/11/06	RMA	Trimble NetRS	4424234797	1.1-3			
PTGV	4/3/06	Update FW	Trimble NetRS	4424234797	1.1-5			
PTGV	6/12/07	Change Radome				ASH700936D_M Radome SCIS 0407	11767	0
PTGV	08/20/10	Update FW	Trimble NetRS	4424234797	1.2-0			
PTGV	5/20/11	Update FW	Trimble NetRS	4646125547	1.3-1			
PTGV	5/16/2017	Update FW	Trimble NetRS	4646125547	1.3-2			
PTGV	5/8/2019	Receiver antenna swap	Septentrio PolaRx5	3046566	5.2.0	SEPPOLANT_X _MF No radome	14505	0
PTGV	9/24/2019	Fw update		5.3.0				
PTGX	6/1/2006	Install	Trimble NetRS	4503244060	1.1-3	ASH701945D_M , Radome SCIT	CR620022304	0.0083
PTGX	7/9/2006	Update FW			1.1-5			
PTGX	5/26/2011	Update FW			1.3-1			

PTGX	12/13/2013	Change receiver	Trimble NetR9	5230K51058	4.81			
PTGX	9/26/2014	Change receiver	Trimble NetRS	4632120770	1.3-1			
PTGX	9/7/2016	Update FW			1.3-2			
PTGX	2/3/2017	Change receiver	Trimble NetRS	4912167722	1.3-2			
PTGX	5/8/2019	Receiver antenna swap	Septentrio PolaRx5	3046476	5.2.0	SEPPOLANT_X _MF No radome	14456	0
PTGX	10/17/2019	Receiver swap	Septentrio PolaRx5	3051446	5.3.0			
RLAP	3/15/1997	Install	Ashtech Z-12	LP00493	CC00	ASH700936D_M w/ Snow Dome	11762	0
RLAP	6/16/00	Change receiver	Ashtech Z-12	LP03441	CD00			
RLAP	7/21/01	Change receiver	Ashtech Z-12	LP03375	CD00	ASH700936D_M w/ Snow Dome	CR52002501	0
RLAP	10/2/03	Change receiver	Ashtech Z-12	LP03440		ASH700936D_M w/ Snow Dome	CR520000401	0
RLAP	5/17/05	Change receiver	Trimble NetRS	4427235680				
RLAP	6/8/05	Solar only conversion	Trimble NetRS	4427235680				
RLAP	6/21/05	Change receiver	Trimble NetRS	4427235630	1.1-3			
RLAP	6/30/05	Update FW	Trimble NetRS	4427235630	1.1-2			
RLAP	4/3/06	Update FW	Trimble NetRS	4427235630	1.1-5			
RLAP	9/15/06	Change receiver	Trimble NetRS	4632120758	1.1-5			
RLAP	6/5/07	Change Radome				ASH700936D_M Radome SCIS 0411	CR520000401	0
RLAP	4/28/09	Change receiver	Trimble NetRS	4427235647	1.1-5			
RLAP	5/26/09	Change receiver	Trimble NetRS	4718131954	1.1-5			
RLAP	8/9/09	Change antenna				ASH701945E_M Radome SCIS 0411	CR520022108	
RLAP	5/8/11	Update FW	Trimble NetRS	4718131954	1.3-1			
RLAP	5/11/2017	Replace Receiver	Trimble NetRS	4644124587	1.3-2			
RLAP	11/28/17	Replace Radome				ASH701945E_M Radome SCIS 0420	CR520022108	0
RLAP	6/3/2017	Receiver swap	Trimble NetR9	5112K74584	5.20			
SCCF	11/24/2019	Install	NetRS	4431236763	1.3-2	Trimble Zephyr II	2615117146	0
STLE	3/1/00	Install	Ashtech Z-12	LP03369		ASH700936D_M w/ Snow Dome	CR520000402	0
STLE	9/10/06	Change receiver	Trimble NetRS	4611206678	1.1-5			

STLE	6/5/07	Change Radome				ASH700936D_M Radome SCIS 0402	CR520000402	0
STLE	09/19/07	Wireless comms installed	Trimble NetRS	4611206678	1.1-5			
STLE	5/10/11	Update FW	Trimble NetRS	4611206678	1.3-1			
STLE	9/4/12	Change receiver	Trimble NetR9	5207K82122	4.61			
STLE	4/3/15	Update FW	Trimble NetR9	5207K82122	4.85			
STLE	4/16/2019	Receiver antenna swap	Septentrio PolaRx5	3046607	5.2.0	SEPPOLANT_X _MF	14504	0
STLE	9/24/2019	Fw update			5.3.0			